Numerical simulations of oil spill trajectories in the Danjiangkou Reservoir in China

Libin Chen, Zhifeng Yang*, Haifei Liu, Chunhui Li

State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China

**Corresponding author's e-mail: zfyang@bnu.edu.cn*

Abstract

Oil spills in surface water happen each year in the world and significantly damage water quality and ecosystems. Numerical simulation of oil spill trajectories is helpful for risk assessment and risk controlling. Previous research for tracking oil spills generally focused on the sea, and not on the great reservoir. Danjiangkou Reservoir, the source reservoir of China's South-to-North Water Diversion Middle Route Project, will flood impounded areas and raise the water to 170 m, a much higher level. The result will be convenient for waterway transportation, but it will also increase the risk of oil spills into the reservoir. In order to efficiently protect the reservoir's water quality and ecosystem, a numerical simulation based, oil spill tracking model was developed and utilized for trajectory simulations of oil spills from five possible sites. Scenarios analysis method was applied to studding the effects of multiple environmental factors on the trajectories of oil parcels in the reservoir. The results indicated that initial water level, wind speed, wind direction and dam operation can obviously affect the spread trajectories of oil parcels in the reservoir. The results can be useful for risk assessment and risk controlling of the oil spills in the reservoir.

Keywords: Danjiangkou Reservoir, numerical simulation, oil spill, risk assessment

Introduction

Oil spill in surface water happen each year in the world and it have been verified to be a significant threat to the environment, with the potential to cause serious environmental and ecological disasters (Carrera-Mart ńez *et al*., 2010; Moreno *et al*., 2011; Bi and Si, 2012; Joydas *et al*., 2012; Stevens *et al*., 2012 and Kennedy and Cheong, 2013). Therefore, emergency responses for controlling oil spills and protecting the environment are urgently needed (Xu *et al*., 2013). Modeling the trajectory of oil parcels before and/or after oil spills have occurred is critical to both emergency planning and risk controlling (Marta-Almeida *et al*., 2013 and Sayol *et al*., 2014). Many numerical models have thus been built and used to simulation of the trajectories of oil parcels (Guo *et al*., 2009; Wang *et al*., 2010; Berry *et al*., 2012; El-Fadel *et al*., 2012; Xu *et* *al*., 2012 and Liu and Sheng, 2014), however, previous research has focused largely on ocean areas, and followed after an oil spill had already occurred. Related research that focused on inland reservoir areas; that was aimed at preventing disasters before they happened; and that took place before an oil spill disaster had occurred, have been rare. Though the volume of oil spills in inland reservoirs may be less than that in oceans, the inland oil spills can significantly damage the water quality and ecosystem of a reservoir, and threaten human health, especially in a reservoir that supplies drinking water. Additionally, predicting the trajectories of oil spills in a reservoir is quite different from predicting those in oceans, because the currents that force oil parcels to move in a reservoir can be regulated by dam operations. Numerical models are necessary to adequately simulate the potential trajectory of oil spills in a reservoir, in order to develop effective emergency planning to protect the reservoir environment, especially in a reservoir that serves the public interest.

Danjiangkou Reservoir, the source reservoir of China’s famous South-to-North Water Diversion Middle Route Project (S-N-M Project), is such a public interest reservoir. The reservoir dam has been elevated to a height of 176.6 m and the water level may thus be raised to a much higher altitude than it was previously. This will provide an opportunity for aquatic traffic in the reservoir, but it will also increase the risk of oil spills in the reservoir. The reservoir is surrounded by vital Chinese roadways, and many bridges stretch across the reservoir and its tributaries. These bridges are potential oil spill sites, considering the tankers that travel across them, and the potential, in any accident, for spilled oil to rush into the reservoir. Once an oil spill accident has occurred, it will damage the water quality and threaten the water transfers. It could induce a public panic in those impacted by or concerned about China’s S-N-M Project. Issues of intense public concern would generate many questions regarding subjects such as the length of time until the oil parcels would reach vulnerable areas; whether the oil spill might damage the water transfers; whether the water transfers should be stopped as soon as an oil spill has occurred, or how to best plan the emergency responses for controlling the oil spill and protecting the public interests and the reservoir environment.

In order to assist in answering these types of questions, a Lagrange particle tracking model was built and applied to the Danjiangkou Reservoir situation, based on a three-dimensional hydrodynamic model. Five potential oil spill sites were identified, along with the scenarios that might force oil parcel movements, including increased water levels, outflow stoppages, and various wind speeds and directions.

Materials and methods

Study area

The Danjiangkou Reservoir, constructed in 1958, was one of the largest reservoirs in Asia at that time, and is the source reservoir of China’s S-N-M Project. In order to fulfill the water transfers, the Danjiangkou Dam was elevated from 162 m to 176.6 m, and the normal water level was elevated from 157 to 170 m. The Taocha Dam is the water transfer dam, located at the northeast end of the reservoir, far away from the Danjiangkou Dam, as shown in Figure 1. The reservoir's four main tributaries are the Han River, the Guanshan River, the Lang River and the Dan River, and its three smaller tributaries are the Si River and the Jian River. The inflow from these three smaller tributaries is relatively small, and was ignored in the hydrodynamic model of the Danjiangkou Reservoir. There are four important bridges across the reservoir; the Jiangbei Bridge, the Lang River Bridge, the Jian River Bridge and the Yun City Bridge near the Chenjiapo boundary site, as shown in Figure 1. These bridges are potential oil spill sites due to the potential for a traffic accident resulting in vehicles, including oil tankers, crashing into the reservoir. There are two important wharfs in the reservoir, the Song Gang wharf and the Danjiangkou wharf, which are also considered to be potential oil spill sites.

Figure 1. The location of the Danjiangkou Reservoir and the potential oil spill sites (a, b, c, and d)

Model description and set-up

The Environment Fluid Dynamics Code (EFDC) was utilized to simulate the trajectories of oil spills in the Danjiangkou Reservoir. The code is a general-purpose modeling package for simulating three-dimensional flow, transport, and biogeochemical processes in surface water systems, which includes reservoirs, lakes, rivers, estuaries, wetlands, and near-shore to shelf scale coastal regions (Hamrick, 1992). The EFDC is now being supported by the US Environmental Protection Agency (EPA). It provides the capability of simulating trajectories of oil spills using the well-known Lagrange particle tracking algorithm (Dynamic Solutions, LLC, 2009). The algorithm considers the oil to be a collective body composed of many oil parcels. The oil parcels are driven by surface currents. Detailed information regarding the EFDC and the Lagrange particle tracking algorithm can be obtained from various research literature (Hamrick, 1992; Tetra Tech, Inc., 2007; Dynamic Solutions, LLC, 2009).

In this study, the surface current was obtained from a three-dimensional hydrodynamic model of the Danjiangkou Reservoir. The three-dimensional hydrodynamic model had a total of 60,000 quadrilateral grids; 10,000 grids in the horizontal plane and 6 vertical layers. The simulated water level values matched the observed values very well with a correlation coefficient (R^2) of 0.99801 (as shown in the left sub-figure in Figure 2), which indicated that the water balance function of the hydrodynamic model performed very well. The flow direction function for the surface of the reservoir also performed reasonably, as shown in the right sub-figure in Figure 2. These results indicated that the hydrodynamic model could be used to build the oil spill tracking model.

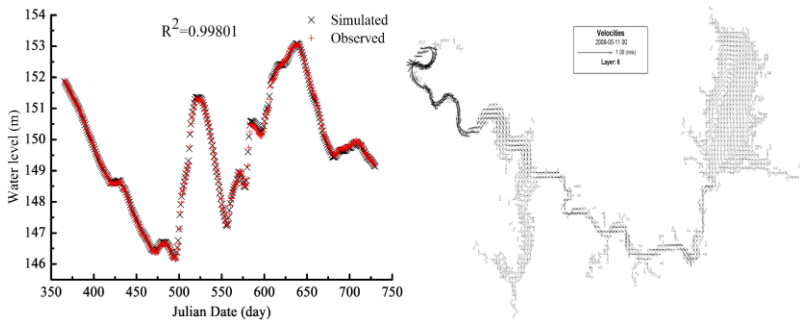

Figure 2. The time series of simulated water levels (cross) and the observed data (plus) at the Danjiangkou Dam area, and the simulated flow direction on May 11, 2009

The five potential oil spill sites identified in this reservoir were; the Yun City Bridge; the Jian River Bridge; the Lang River Bridge; and the Danjiangkou wharf, which includes the Jiangbei Bridge, and the Songgang wharf, respectively. The initial conditions for the particle tracking model were set using the data from May 5, 2009. This day was within the tourist season, when there are normally many travelers rushing to the reservoir area for cruises, which creates an additional risk of oil spills from cruise ships. Traffic transportation at the Danjiangkou Reservoir area is, however, typically quite busy in May, which also adds a higher risk of traffic accidents. In each potential oil spill site, 1,000 parcels were released before the model was executed. The movement of oil parcels in a vertical direction in the reservoir was fixed at 0.2 m below the water surface, taking into consideration the buoyancy of the oil.

Simulation scenarios

Prior to establishing the simulation scenarios, the frequencies of 16 different wind directions and speeds during the month of May for the most recent thirty years were analyzed. The results showed that the top three most frequent wind directions were 135°, 157.5°and 315°(Figure 3), and the average wind speed was 1.5 m/s.

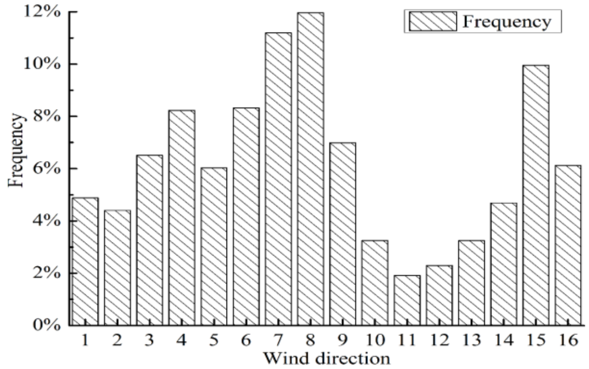

Figure 3. Frequencies for wind directions in May of the most recent thirty years in the Danjiangkou Reservoir area

The simulation scenarios included increasing the initial water level, stopping the outflows, considering different wind speeds and directions, and simulating spatial and temporal patterns of oil parcels during the top three wind directions.

Increased initial water levels

The normal water level of the reservoir would be raised to 170 m. In order to explore whether increased water levels could affect the trajectories of oil spills in the reservoir, three models with different initial water levels were simulated. The initial water levels were 145 m, 155 m, and 165 m, respectively. While operating these models, the wind speed was maintained at 1.5 m/s, and the wind direction was maintained at 135°.

Stopping outflows

The two main outflows from the reservoir were from the Danjiangkou Dam and the Taocha Dam. Their operation could adjust the surface current in the reservoir, and thus affect the trajectories of the oil parcels. One scenario involved stopping outflow from the Taocha Dam, and another involved stopping outflow from the Danjiangkou Dam. The initial water level was 155 m, while the wind direction and wind speed were maintained at 135 °and 1.5 m/s, respectively.

Different wind speeds and directions

The wind is the main force that drives the oil parcel movements within the reservoir (Bi and Si, 2012; Liu and Sheng, 2014). The four wind directions that were simulated in this study were north, east, south and west. The six wind speeds simulated were 0, 0.5, 1.0, 1.5, 2.0 and 2.5 m/s. In the wind direction models, the wind speed was maintained at 1.5 m/s; and in the wind speed models, the wind direction was maintained at 135°. The initial water level was 155 m for both models.

Temporal and spatial patterns of the oil parcels during the top three most frequent wind directions

With the goal of predicting the oil spill trajectories and the expected times that the oil parcels would reach the vulnerable areas of the reservoir, the temporal and spatial patterns of the oil parcels were simulated. These results would be critical in planning effective and timely responses for controlling oil spills in the reservoir. The top three most frequent wind directions were used, the wind speed was maintained at 1.5 m/s, and the initial water level was 155 m.

Results and discussions

In this study, the variables of increasing initial water levels, stopping outflows, and applying different wind speeds and directions, have been shown to significantly affect the trajectories of the oil parcels in the reservoir

The effects of increasing initial water levels

As shown in Figure 4, the oil parcels that were located in the Chenjiapo, Jian River, and Lang river areas, each enlarged as the initial water level increased. However, this effect did not seem to be the case for the Danjiangkou and Songgang wharf areas. It was interesting that the oil parcels from the potential oil spill site at the Songgang wharf moved more slowly during the higher initial water levels. The oil parcels from the Songgang wharf could reach the Taocha head canal 15 days after the oil spill, at an initial water level of 145 m, however for conditions of 155 m and 156 m of initial water levels, the oil parcels needed more time to reach the Taocha head canal. An explanation for the different effects may be that the outflow in the Taocha Dam exerted less effect on the surface current in this area of the higher water levels. The reduced current exerted less effect on the oil parcels. This finding is important to the risk assessment of the oil spills in the reservoir. It demonstrates that the oil spills in the reservoir will have less potential damage to the S-N-M Project after the water level has increased. Additionally, it was noted that the increased water level would also reduce the risk of oil spills moving onto the beach habitat of the reservoir, because there would be more time for a clean-up of the oil parcels before they reached the vulnerable areas near higher waters.

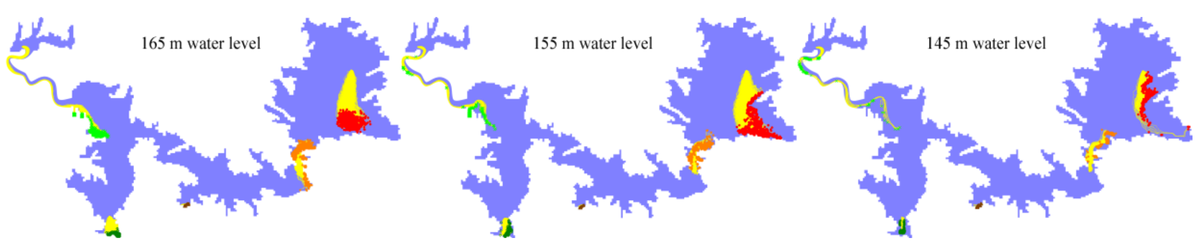

Figure 4. Oil spill trajectories at three initial water levels (the yellow color is the oil spill trajectories, and the other colors at the end of the oil trajectories are the locations of the oil parcels after 15 days, from different potential oil spill sites)

The effects of stopping outflows

As shown in Figure 5, stopping the outflow from the Taocha Dam obviously affected the trajectories of oil spills from the Songgang wharf. It reduced the speed of the movement of the oil parcels toward the Taocha head canal, which was attributed to the halted outflow from the Taocha Dam reducing the surface current. After stopping outflow from the Taocha Dam, the driving force that moved the oil parcels on the surface of the reservoir would be the wind speed, and not the outflow induced current. It was then noted that stopping the outflow in the Danjiangkou Dam had little effect on the oil parcels from all the potential oil spill sites. This finding is important to emergency planning for the reservoir after oil spills have occurred. Stopping outflow in the Taocha Dam will help to control oil spills, but it would also stop water transfers. It will damage economic and ecological benefits to northern China. If the volume of the oil spill is small, it would not be necessary to stop outflows, since the oil parcels would move slowly in the reservoir under average wind speeds. It would take more than 15 days for the oil parcels to reach the Taocha head canal, giving enough time to control the oil parcels in the reservoir.

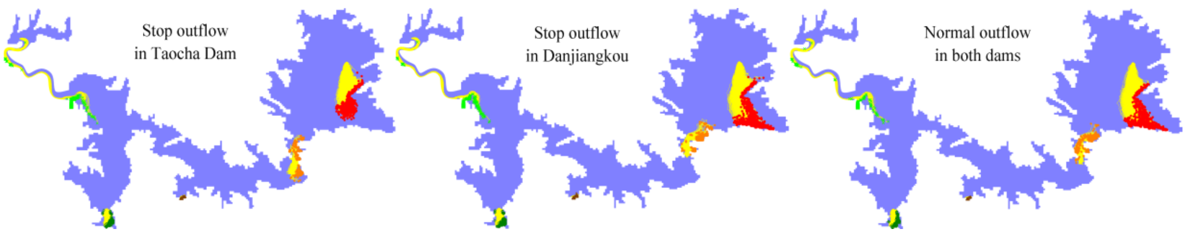

Figure 5. Oil spill trajectories in the scenarios with outflow stoppages (the yellow color is the oil spill trajectories, and the other colors at the end of the oil trajectories are the locations of the oil parcels after 15 days, from different potential oil spill sites)

The effects of wind speeds and directions

As demonstrated in Figure 6, the wind direction obviously affected the trajectories of the oil parcels. The oil parcels moved with the wind directions. It was noted that a north wind extended the trajectories of the oil parcels from the potential oil spill sites of the Chenjiapo and the Lang River. This meant that a north wind would increase the risks of oil spills in the reservoir. Fortunately, this could not threaten the Danjiangkou Dam area, or the Taocha area, but would only add to the difficulties of cleaning up the oil slick in the reservoir.

As shown in Figure 7, the wind speed obviously affected the trajectories of oil spills in the reservoir. A wind speed below 2 m/s could not make the oil parcels move to the Taocha head canal within 15 days after the oil spills, indicating that there would be more time to clean the oil parcels in the reservoir during low wind speeds. However, more efforts should be exerted for speedily cleaning the oil parcels in the reservoir during high wind speed conditions, especially at wind speeds greater than 2 m/s.

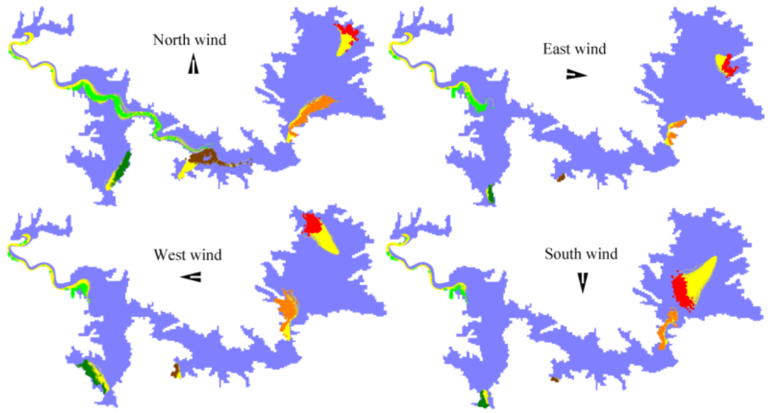

Figure 6. Oil spill trajectories for different wind directions (the yellow color is the oil spill trajectories, and the other colors at end of the oil trajectories are the locations of the oil parcels after 15 days, from different potential oil spill sites)

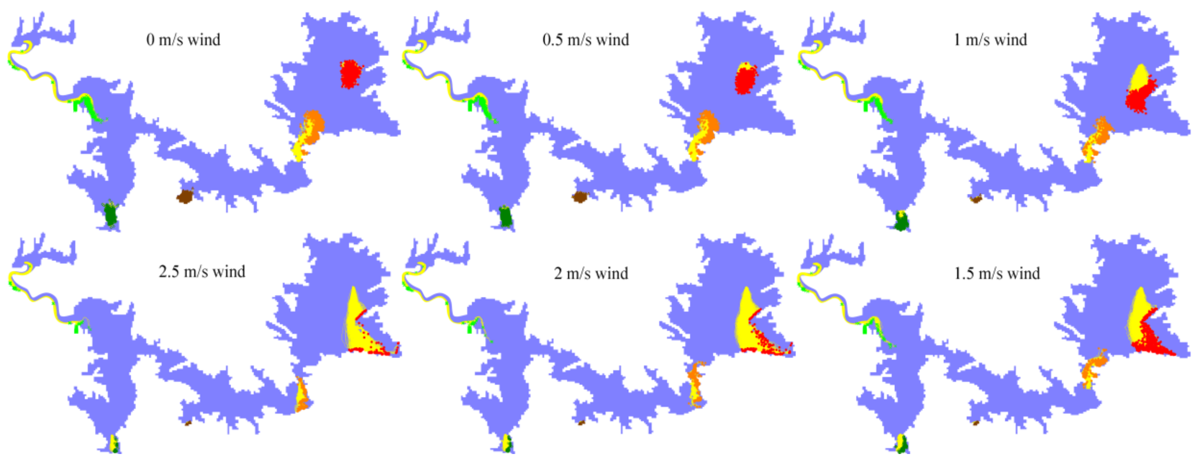

Figure 7. Oil spill trajectories during different wind speeds (the yellow color is the oil spill trajectories, and the other colors at the end of the oil trajectories are the locations of the oil parcels after 15 days, from different potential oil spill sites)

Temporal and spatial patterns of oil parcels for the top three most frequent wind directions

As shown in Figure 8, the oil parcels moved slowly in the reservoir under average wind speeds. Two days after the oil spills, the oil parcels had only moved a small amount. Seven days after the oil spill, the oil parcels from the Songgang wharf had not yet reached the southeast beach of the reservoir. Additionally, as shown in Figure 8, the oil parcels from the Chenjiapo area, the Jian River, the Lang River and the Danjiangkou wharf could not affect the Taocha head canal within 15 days after the oil spills. As the Han River is a winding river in the Danjiangkou Reservoir area, it would be easy to control the oil spills within the reservoir, meaning that an oil spill from the Han River would not be a threat to water transfers. Furthermore, as shown in Figure 8, the oil parcels coming from the Songgang wharf were not moved directly to the Taocha head canal by the three most frequent wind directions for the month of May. This indicates that an oil spill in May would not be a threat to the Taocha head canal if enough efforts were exerted to control the oil spill within the reservoir. As the Danjiangkou Reservoir is an important, public interest reservoir, the local government would provide enough manpower to monitor and control the oil spills in the reservoir.

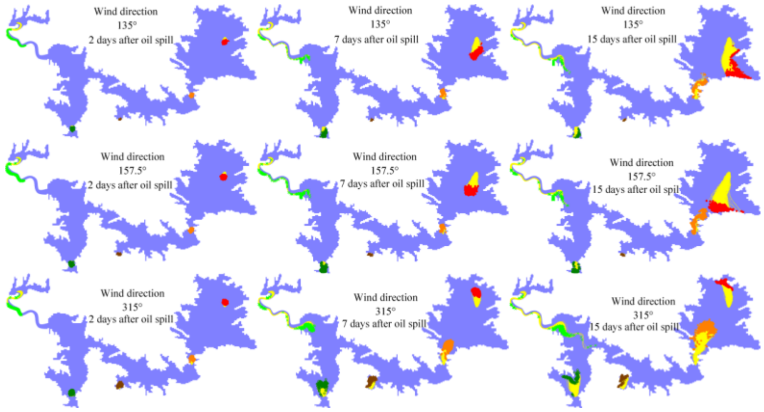

Figure 8. Temporal and spatial patterns of oil parcels during the top three most frequent wind directions (the yellow color was the oil spill trajectories, and the other colors at ends of the oil trajectories are the locations of the oil parcels after 15 days, from different potential oil spill sites)

Conclusions

A numerical model based on the Lagrange particle tracking algorithm was constructed and successfully applied to the Danjiangkou Reservoir for simulating the trajectories of oil spills from five potential spill sites. The scenarios included increased initial water levels, stopping outflows, and considerations of different wind speeds and directions. The results showed that the increased initial water level would reduce the risk of oil particles being transported to the Taocha head canal. At the emergency stage of an oil spill in the Danjiang part of the reservoir, stopping the outflow in the Taocha Dam would greatly reduce the risk of oil particles being transported to the Taocha head canal. The oil parcels were sensitive to wind speeds and wind directions in the reservoir. The oil spills in May would present a low risk to the Taocha head canal, because the oil parcels moved slowly in the reservoir under wind speeds averaged from multiple-years, and they were not moved directly to the Taocha head canal under the top three most frequent wind directions for the month of May, for the recent thirty years.

Acknowledgments

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